

Silicon-based heterogeneous photonic integrated circuits for the mid-infrared

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Abstract: In this paper we elaborate on our work in the field of mid-infrared photonic integrated circuits for spectroscopic sensing applications. We discuss the use of silicon-based photonic integrated circuits for this purpose and detail how a variety of optical functions in the mid-infrared besides passive waveguiding and filtering can be realized, either relying on nonlinear optics or on the integration of other materials such as GaSb-based compound semiconductors, GeSn epitaxy and PbS colloidal nanoparticles.

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1. Introduction

Silicon photonics is emerging as a key enabling technology for the realization of highly integrated photonic circuits. While originally conceived for datacom and telecom applications [1], the scope of potential applications has in recent years broadened to the use of silicon photonic integrated circuits for sensing [2] and biomedical instrumentation [3]. However, in these applications one typically holds on to using the telecommunication wavelength range (1.3-1.55 μm) for implementing these functions. Especially in the field of optical sensing, stepping away from this wavelength range could enable the realization of a whole new class of devices with unprecedented sensitivity and selectivity by exploiting the very specific and strong absorption features of molecules in the mid-infrared (2-8 μm) [4]. Such spectroscopic sensing systems are envisioned to be used in handheld applications, requiring a compact, rugged and low power consumption solution, which makes an integrated approach very attractive. Therefore, in this paper we will elaborate on the technological developments and demonstrations that we have recently achieved in the field of silicon-based mid-infrared photonic integrated circuits and devices. The paper is organized as follows: in Section 2, mid-IR passive silicon-based waveguide circuits are presented, Section 3 deals with the use of these waveguide structures for nonlinear optics based mid-infrared light generation (parametric amplification, parametric oscillation and supercontinuum generation) and upconversion, while Section 4 to 6 deals with the integration of other materials (GaSb-based compound semiconductors, GeSn epitaxy and PbS colloidal nanoparticles) on top of the silicon waveguide circuit to complement the functionality that can be realized purely in silicon.

2. Passive silicon-based waveguide circuits for the mid-infrared

Silicon photonic integrated circuits for the telecommunication wavelength window are typically realized on silicon-on-insulator wafers, due to the high refractive index contrast between the silicon core and SiO_2 or air cladding that is available on this platform. This allows the realization of compact photonic integrated circuits leveraging the well-developed CMOS fabrication infrastructure. Therefore, it makes sense to evaluate how far the wavelength range of operation can be pushed into the infrared using such a platform. While silicon itself is transparent up to about 8 μm wavelength, the SiO_2 buried oxide layer starts to absorb heavily around 4 μm wavelength, thereby limiting the silicon-on-insulator transparency range from 1.1 to 4 μm [5]. Moreover, care should be taken that the SiO_2 buried oxide layer thickness is sufficiently thick to avoid substantial substrate leakage, especially at longer wavelengths. SOI wafers with a 220nm thick silicon device layer are emerging as a standard for telecommunication wavelength range applications. Therefore, in order to exploit as much as possible the already developed technology, waveguide circuits for the short-wave infrared (2-2.5 μm) can best be implemented on this platform. For longer wavelengths the silicon device layer thickness becomes too thin and thicker waveguide layers should be used. On the 220nm SOI platform several basic passive optical components were realized for the 2-2.5 μm wavelength range that can be used in a spectroscopic sensing system. This includes high index contrast waveguides with low optical loss (0.5dB/cm) [6], high efficiency (3.8dB insertion loss) fiber-to-chip grating couplers [6], ring resonators with a Q-factor of 10^5 [7] and wavelength (de)multiplexers based on arrayed waveguide gratings and echelle gratings [8]. Performance metrics representative for these different devices are shown in Figure 1. Figure 1(a) shows the optical waveguide loss of a 900nm wide and 220nm high air clad silicon wire in the 2.1 to 2.3 μm wavelength range for the fundamental TE mode. The TE polarization fiber-to-chip coupling spectrum (using standard single mode fiber SMF-28 in the 2-2.5 μm wavelength range) of a silicon grating coupler structure is shown in Figure 1(b) illustrating a 90nm 3dB bandwidth. The through port spectrum of a high Q ring resonator implemented on this platform is shown in Figure 1(c), while Figure 1(d) shows a 6 channel arrayed waveguide

grating wavelength demultiplexing characteristic. All these components are fabricated using standard CMOS fabrication technology on 200mm SOI wafers alongside photonic integrated circuits for the telecommunication window.

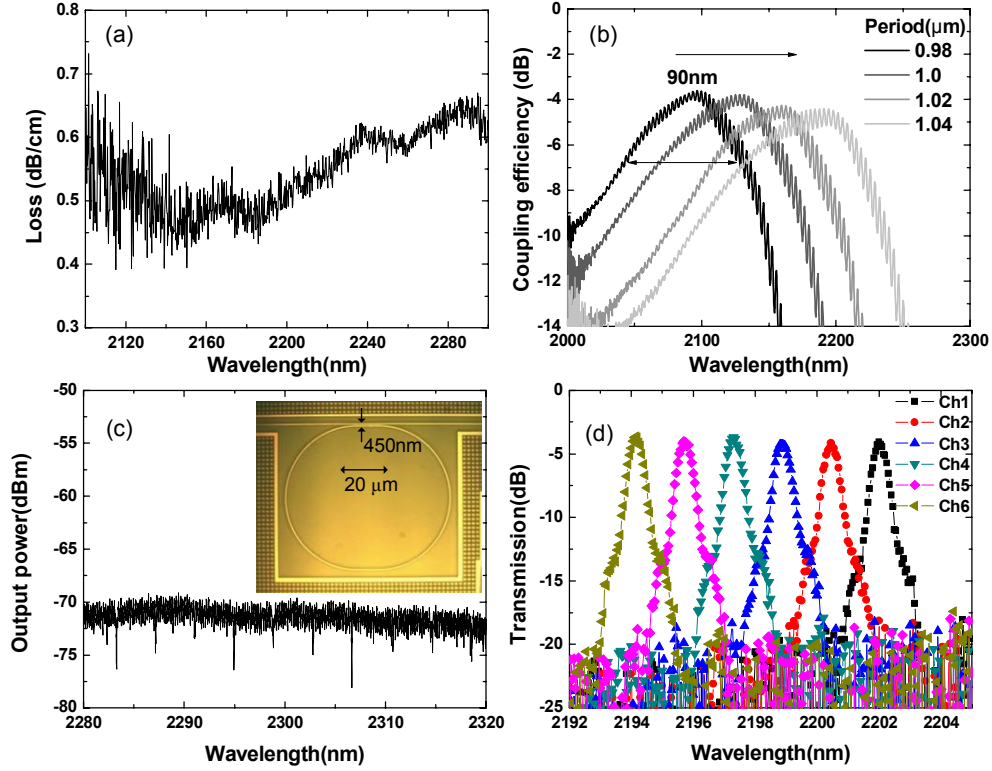


Figure 1: (a) Waveguide loss as a function of wavelength for a 900nm by 220nm air clad single mode silicon waveguide (fundamental TE mode); (b) fiber-to-chip grating coupler efficiency spectrum for TE polarized light; (c) transmission spectrum of an all-pass ring resonator in the 2.3μm wavelength range; (d) wavelength (de)multiplexing characteristic of an arrayed waveguide grating device.

While the 220nm thick silicon waveguide platform already allows implementing several optical functions with good performance, a larger flexibility in device geometry can be obtained if an additional layer of poly-silicon can locally be added on top of the 220nm silicon device layer. This is, for example, the case for the fiber-to-chip grating coupler that was discussed above [6]. Moreover, this availability of a thicker silicon device layer allows extending the wavelength range of operation to the 4μm wavelength transparency edge of the platform. This was demonstrated in [9] where we realized low-loss silicon waveguides operating at 3.8 μm wavelength and high-performance wavelength (de)multiplexer circuits, as shown in Figure 2. While the losses at 3.8 μm on the 220nm crystalline silicon / 160nm polycrystalline silicon platform for a 1.45 μm wide single mode waveguide are around 6dB/cm (WG2), better performance can be obtained with a fully crystalline Si device layer, since the Rayleigh scattering losses in the poly-crystalline silicon can be avoided this way: propagation losses in the range of 3-4dB/cm are obtained (WG1).

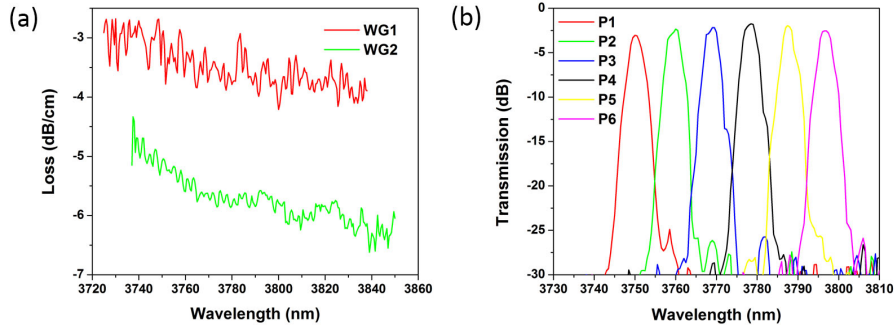


Figure 2: (a) Silicon-on-insulator waveguide losses in the $3.8\mu\text{m}$ wavelength range for 400nm c-Si waveguide layers (WG1) and 220nm c-Si/160nm p-Si (WG2); (b) example of an arrayed waveguide grating wavelength demultiplexer operating at $3.8\mu\text{m}$ implemented on the 220nm c-Si/160nm p-Si platform.

Beyond $4\mu\text{m}$, wavelength alternative waveguide platforms need to be explored. Several approaches can be followed. Silicon-on-sapphire waveguide circuits can be used, which still allow exploiting the high refractive index contrast between the silicon waveguide core and the sapphire substrate [10]. The transparency window is in this case limited to about $5.5\mu\text{m}$ wavelength. An alternative is the use of free-standing silicon waveguide structures, allowing access to the full transparency window of silicon up to $8\mu\text{m}$ wavelength [11]. Such an approach is however less flexible with respect to the type of structures that can be made free-standing given the required sideways underetching of these waveguide structures. Another platform that can be used is Ge on Si. Since the epitaxial growth of germanium on silicon is well mastered both for optical and electronic applications, Ge films of high quality can be used as the waveguide core, despite the large lattice constant mismatch between germanium and silicon. Given the broad transparency range of germanium in the infrared (up to $14\mu\text{m}$) this seems like a very attractive solution for photonic integrated circuits operating beyond $4\mu\text{m}$ wavelength. Recently we demonstrated 3dB/cm waveguide losses in the $5\text{--}5.5\mu\text{m}$ wavelength range on this platform and the realization of basic optical components, which can be used, for example, in the wavelength multiplexing of arrays of quantum cascade DFB lasers, such as Mach-Zehnder interferometer structures, as shown in Figure 3 [12].

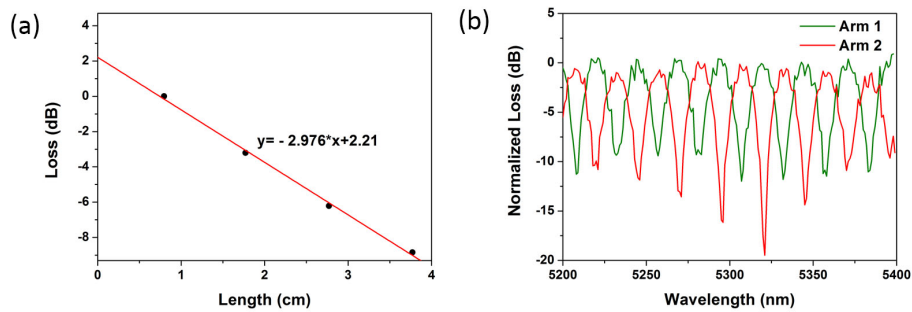


Figure 3: (a) Ge-on-Si waveguide normalized losses at $5\mu\text{m}$ wavelength for a $2\mu\text{m}$ thick germanium device layer thickness ($2.2\mu\text{m}$ waveguide width, completely etched through the germanium waveguide core). (b) Mach-Zehnder interferometer implemented in Ge on Si for wavelength multiplexing purposes.

3. Nonlinear optics on a silicon photonics platform in the mid-infrared

3.1 Introduction

While silicon photonics provides a good platform for the implementation of passive linear waveguide circuits such as the ones elaborated on in Section 2, a broad range of novel functionalities can be implemented on a chip when one exploits the strong nonlinear response of high index contrast silicon photonic waveguides. This was already recognized for telecommunication applications, given the tight confinement in a sub-micron size silicon waveguide and the intrinsically high Kerr nonlinearity of silicon. However, the performance of such silicon devices in the telecommunication wavelength range is severely limited due to parasitic two-photon absorption. A major advantage of working at longer wavelengths, and specifically in the 2-2.5 μm wavelength range, is that two-photon absorption and the associated free carrier absorption can be substantially reduced, making silicon photonic waveguide circuits ideal for the implementation of nonlinear optical functions. In the subsequent sections we will elaborate on nonlinear functionalities that were implemented in the short-wave infrared (2-2.5 μm), both in crystalline and hydrogenated amorphous silicon.

3.2 Nonlinear optics in crystalline silicon

The strong third order nonlinearity of silicon, combined with the tight optical confinement, the large freedom in dispersion engineering of silicon photonic wire waveguides and the absence of parasitic two-photon absorption above 2.2 μm makes silicon-on-insulator waveguide structures ideal for implementing four-wave-mixing based nonlinear functions. When a high intensity electromagnetic wave is present in a third order nonlinear medium, a process called modulation instability can occur [13], which basically relates to the parametric amplification of background noise in wavelength bands around the pump (a signal wavelength band on the short wavelength side and an idler wavelength band on the long wavelength side of the pump). The exact position (and the mere occurrence of this parametric amplification) is determined by the dispersion of the silicon photonic waveguide. Efficient parametric amplification will occur when

$$\Delta k_{lin} + 2\gamma P = 0, \quad (1)$$

in which Δk_{lin} is the linear phase mismatch between the signal, idler and pump wave ($\Delta k_{lin} = k_s + k_i - 2k_p$). $2\gamma P$ is the nonlinear phase mismatch term, in which P is the (peak) power of the pump beam in the silicon waveguide and γ is the nonlinear parameter of the silicon waveguide ($\gamma = n_2 \omega / A_{eff} c$, with n_2 the nonlinear refractive index and A_{eff} the effective waveguide cross-section). Expression (1) can be rewritten by considering the Taylor expansion of the waveguide dispersion relation $k(\omega)$ around the pump wavelength

$$k(\omega) = k(\omega_p) + \beta_1(\omega - \omega_p) + \frac{1}{2}\beta_2(\omega - \omega_p)^2 + \dots, \quad (2)$$

with $\beta_i \triangleq \left. \frac{d^i k}{d\omega^i} \right|_{\omega=\omega_p}$. By making use of the fact that $\omega_s - \omega_p = \omega_p - \omega_i = \Omega$ due to energy conservation, we can rewrite equation (1) up to fourth order as

$$\beta_2 \Omega^2 + \frac{1}{12} \beta_4 \Omega^4 + 2\gamma P = 0. \quad (3)$$

From this phase matching condition several conclusions can be drawn. In the case we consider parametric amplification of wavelengths close to the pump, the fourth order term can be neglected. Therefore, $\beta_2 < 0$ is required to obtain phase matching. This implies that the

waveguide should show anomalous group velocity dispersion. Considering wavelength bands far away from the pump the fourth order term needs to be taken into account and in order to have a solution far away from the pump (large Ω), β_2 and β_4 should be of opposite sign. In the case $\beta_2 < 0$ and $\beta_4 > 0$, both a wavelength band close to the pump (broadband modulation instability) and far away from the pump (narrowband modulation instability) will experience parametric amplification, while in the opposite case ($\beta_2 > 0$ and $\beta_4 < 0$) only narrow band modulation instability far away from the pump should be observed. This is schematically illustrated in Figure 4.

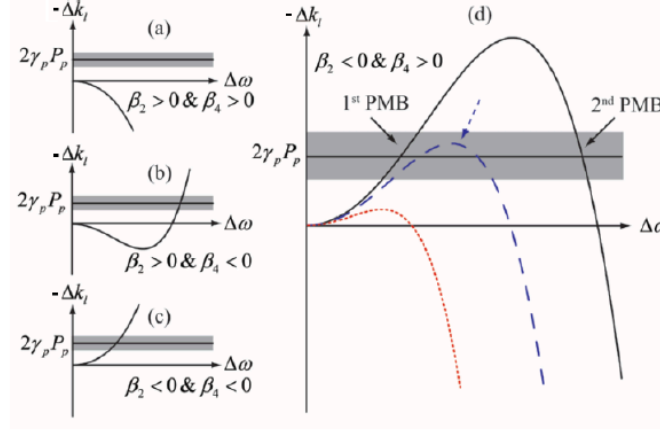


Figure 4: The phase mismatch as a function of detuning frequency from the pump. Depending on the sign of β_2 and β_4 the phase matching equations have several solutions (PMB=phase matching band).

Several device demonstrations were recently realized in silicon photonic waveguide circuits based on parametric amplification due to a strong pump wave in the 2. μm wavelength range, including the demonstration of $>50\text{dB}$ (Raman assisted) parametric gain in a 2cm long silicon photonic wire waveguide (900nm wide, 220nm thick silicon waveguide core) [14], the generation of a 1.5 μm to 2.5 μm spanning supercontinuum [15] and a fiber loop based tunable optical parametric oscillator based on a silicon photonic wire parametric gain element [16]. Narrowband parametric amplification was demonstrated in [17], where the downconversion of a telecom-band signal to the mid-infrared and the upconversion of such a mid-infrared signal to the telecom band was demonstrated. This shows the promise of nonlinear silicon photonic integrated circuits, since it allows the generation and detection of mid-infrared signals based on well-developed telecom-band sources and detectors respectively. These key results are summarized in Figure 5. In all these experiments a 2. μm picosecond pulse train with 76MHz repetition rate generated by a Coherent/MIRA OPO system was used as the pump. Figure 5(a) shows the measured parametric amplification of a continuous wave probe laser in the presence of a 13.5W peak power pulse train at 2.175 μm wavelength in a 900nm wide by 220nm high waveguide (2cm length). A Raman-assisted gain peak larger than 50dB can be observed. Figure 5(b) shows the generation of a mid-infrared to telecom-band supercontinuum in similar 2cm long waveguides, which results from the complex interplay between modulation instability, self-phase modulation, Raman amplification, cascaded four-wave mixing and dispersive wave generation. The four different spectra correspond to a 3.1 W, 4.3 W, 7.9 W and 12.7 W peak power pulse train at 2120nm on the chip. Figure 5(c) shows the tuning characteristic of a synchronously pumped optical parametric oscillator using a silicon photonic wire as the nonlinear gain medium. By adjusting the delay in the fiber feedback loop, wavelength tuning can be realized due to the fiber dispersion. Figure 5(d) illustrates the use of

discrete band modulation instability to upconvert a $2.44\mu\text{m}$ continuous wave signal into the telecommunication wavelength range using four-wave mixing with a pump at 1946nm . This spectral translation enables the detection of mid-infrared radiation using high sensitivity telecom photodetectors operating at room temperature. Using the same four-wave mixing process, also mid-infrared radiation can be generated in this way, based on telecommunication wavelength range (tunable) laser sources.

To illustrate the large degree of freedom in dispersion engineering, and to allow confining longer wavelength idler radiation in the silicon waveguide, narrowband parametric amplification in 400nm thick and 1650 nm wide silicon-on-insulator waveguides was also recently demonstrated. The results showed octave spanning four-wave-mixing and the generation of $3.6\mu\text{m}$ radiation with a $2.19\mu\text{m}$ pump [18].

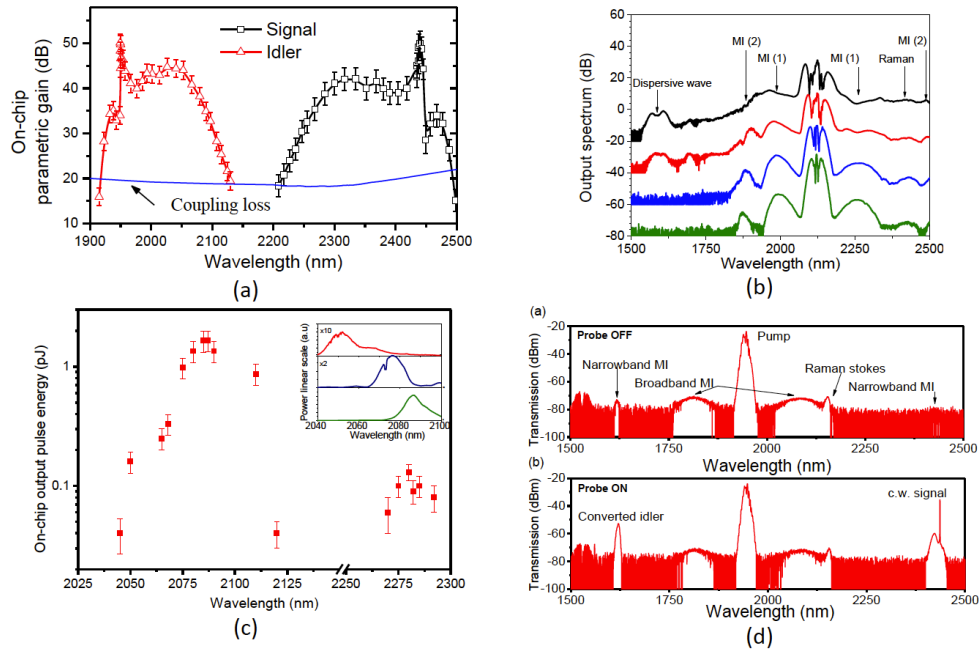


Figure 5: (a) $>50\text{dB}$ Raman assisted parametric amplification in wavelength bands close to the $2.175\mu\text{m}$ pump wavelength; (b) supercontinuum generation in a silicon waveguide due to the complex interplay of modulation instability, self-phase modulation, Raman amplification, cascaded four wave mixing and dispersive wave generation; (c) tuning characteristic of a fiber loop based tunable optical parametric oscillator based on a silicon parametric gain chip; (d) spectral translation between the telecom and mid-infrared wavelength band.

3.3 Nonlinear optics in hydrogenated amorphous silicon

The use of crystalline silicon in the short-wave infrared allows for efficient nonlinear optical processes based on parametric amplification. However, in order to avoid parasitic two-photon absorption a pump wavelength longer than $2.2\mu\text{m}$ is required. This requires the use of bulky optical pump sources such as the OPO system used in the previous experiments. In order to make more compact systems, it would be beneficial to be able to exploit the recently developed Thulium doped fiber lasers and amplifiers operating in the $1.9\text{--}2.0\mu\text{m}$ wavelength range. However, this would result in substantial two-photon absorption in crystalline silicon waveguides. Therefore the use of hydrogenated amorphous silicon waveguide structures was evaluated, given the larger bandgap of hydrogenated amorphous silicon with respect to

crystalline silicon waveguides. The use of hydrogenated amorphous silicon for third order nonlinear optics applications was demonstrated previously in the telecommunication wavelength band, showing a substantially higher nonlinearity and lower two-photon absorption compared to crystalline silicon [19]. However, the material was proven to be unstable under prolonged exposure to the high intensity pump. This was attributed to the Staebler-Wronski effect [20] (well known in the world of amorphous silicon solar cells), in which generated electron-hole pairs in the material recombine close to a weak Si-Si bond resulting in the breaking of the bond and hence in a degradation of the material. However, by operating in the Thulium fiber source wavelength range, no strong parasitic two-photon absorption – and hence electron-hole pair generation – is to be expected in hydrogenated amorphous silicon. This was recently demonstrated by showing the generation of a supercontinuum in an a-Si waveguide using a Thulium fiber laser picosecond pulse source, without observable degradation of the material over time, as shown in Figure 6 [21]. This provides scope for the implementation of compact integrated mid-infrared optical systems based on nonlinear hydrogenated amorphous silicon waveguide structures.

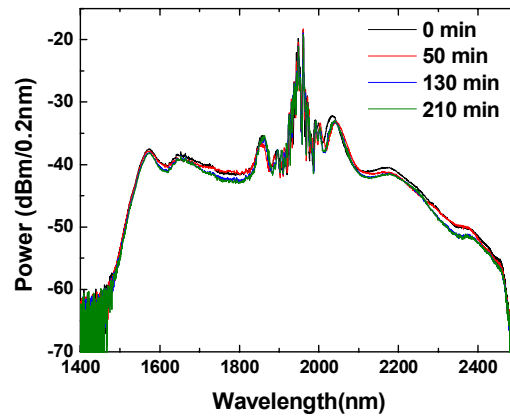


Figure 6: Generation of a supercontinuum in an amorphous silicon waveguide using a Thulium fiber picosecond pulse source at 1950nm wavelength. No degradation of the a-Si can be observed.

4. Monolithically integrated devices

While the passive silicon structures described above provide an excellent platform for mid-IR waveguides, spectral filters and nonlinear optics, there is a need for other integrated components such as mid-infrared photodetectors and laser sources integrated onto the platform. This can be realized in several ways. A very attractive approach in view of cost would be to monolithically integrate such opto-electronic devices on the silicon platform. Germanium-based materials can be used for this purpose. While Ge photodetectors [22] and lasers [23] have been demonstrated on the silicon platform, the bandgap of Ge restricts their use to the telecommunication wavelength band. To extend the operational wavelength range to the mid-infrared, Sn can be added to the germanium matrix in order to reduce its bandgap. Moreover it turns out that adding Sn to the matrix makes the bandgap more direct, providing scope for the realization of group IV-based lasers on the silicon platform [24]. In order to demonstrate the potential of GeSn-based opto-electronic devices, a $\text{Ge}_{0.9}\text{Sn}_{0.1}$ three quantum well structure sandwiched between Ge cladding layers was grown by MOCVD on 200mm silicon wafers and photoconductor operation up to $2.5\mu\text{m}$ wavelength was demonstrated. This is illustrated in Figure 7(a) [25] showing the responsivity of surface illuminated $\text{Ge}_{0.9}\text{Sn}_{0.1}/\text{Ge}$ photoconductors as a function of wavelength and as a function of the number of $\text{Ge}_{0.9}\text{Sn}_{0.1}$ quantum wells. Given the compatibility of this epitaxial growth process with selective area

growth, GeSn-based photodetectors integrated with passive silicon waveguide circuitry (e.g. implementing a wavelength demultiplexing functionality) can directly be envisioned. Also germanium-on-silicon waveguide circuits with monolithically integrated GeSn detectors can be envisioned, given the fact that a Ge buffer layer is grown on the silicon substrate for the GeSn growth, which can act as a waveguide layer in the 2-2.5 μm wavelength range, where the GeSn detectors are sensitive. In order to evaluate the feasibility of such a platform, the propagation losses of a 2.25 μm wide and 1 μm thick germanium waveguide was evaluated in the short-wave infrared, as shown in Figure 7(b). These low losses indicate that such a platform can be envisioned for the realization of monolithically integrated short-wave infrared spectrometers.

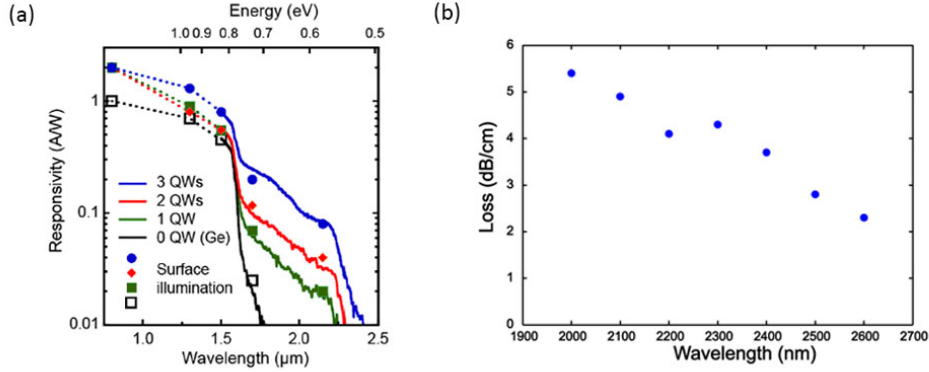


Figure 7: (a) GeSn/Ge photoconductor integrated on a 200mm silicon wafer demonstrating the potential of GeSn heterostructures for the realization of mid-infrared opto-electronic devices on silicon photonic integrated circuits: responsivity as a function of wavelength and as a function of the number of GeSn quantum wells; (b) germanium-on-silicon waveguide losses in the short wave infrared (2.25 μm wide and 1 μm thick germanium waveguide).

5. Heterogeneously integrated III-V on silicon devices and systems

Another approach to integrate mid-IR opto-electronic components on the silicon waveguide platform is by the heterogeneous integration of III-V semiconductor device stacks onto the silicon waveguide circuits. This heterogeneous integration process is by now a well-developed technology for the transfer of InP-based epitaxy onto silicon waveguide circuits, in order to realize integrated laser sources, amplifiers, modulators and photodetectors operating at telecommunication wavelengths [26]. While the emission wavelength of InP-based epitaxy based on band-to-band emission can be stretched to about 2.2 μm , and for photodetectors to a cut-off wavelength of about 2.6 μm using extended InGaAs, a more flexible and further reaching approach would be to integrate GaSb-based epitaxy on the silicon platform, allowing operation in the 2-3.5 μm wavelength range. The use of superlattice structures allows extending the wavelength range of operation even further into the infrared. Therefore, a GaSb-to-silicon heterogeneous integration process was developed based on DVS-BCB adhesive wafer bonding. This process uses the commercial polymer DVS-BCB as an adhesive bonding agent between the silicon waveguide circuit wafer and the III-V material, which is bonded epi-side down to the silicon wafer, after which the GaSb growth substrate is removed by mechanical grinding and wet chemical etching, leaving the GaSb epitaxial film attached to the silicon waveguide circuit. This epitaxial layer can then be processed into an integrated photodetector or laser coupled to the silicon waveguide circuit.

The heterogeneous integration of GaSb photodetectors on silicon waveguide circuits based on this process was recently demonstrated [27,28]. Photodetectors with a cut-off wavelength of

2.5 μm and a responsivity above 1A/W were demonstrated. The integration of an array of such photodetectors on a silicon spectrometer chip as shown in Figure 8(a) and (b) shows the potential of this integration technology for chip-scale integrated spectrometers [8]. The DVS-BCB that is used as a bonding agent has an absorption spectrum as shown in Figure 8(c). A strong absorption in the 3-3.5 μm wavelength band can be observed (due to C-H stretching vibrations). Given the compact size of these photodetectors ($\sim 20\mu\text{m}$ long), this absorption is not expected to have a substantial impact on the device responsivity even when operating at wavelengths beyond 3 μm .

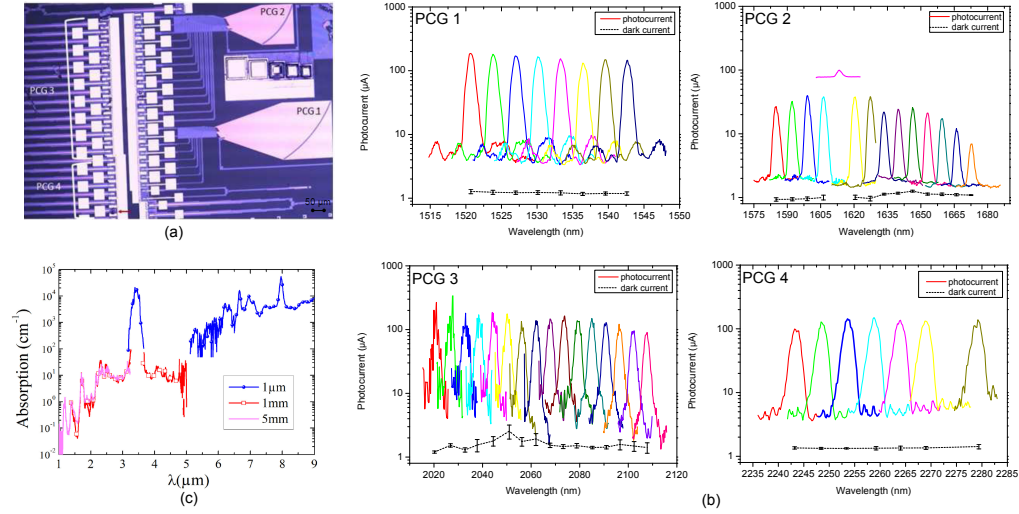


Figure 8: (a) Microscope picture of the heterogeneously integrated photodiode array on top of a planar concave grating spectrometer; (b) representative spectral response (photocurrent versus wavelength) of the different channels of the spectrometer in different wavelength ranges covering 1500nm-2300nm; (c) DVS-BCB absorption spectrum in the mid-infrared wavelength range.

Besides GaSb photodetectors, also GaSb-on-Si laser sources are being developed. However, in this case the DVS-BCB absorption can have a substantial impact on the device performance. This problem can however be mitigated by exploiting a molecular wafer bonding process which is free of organic materials at the bonding interface [26]. Even the direct epitaxial growth of GaSb laser structures on silicon substrates has recently been reported [29,30].

6. IV-VI colloidal quantum dot integration

While III-V semiconductor heterogeneous integration provides an interesting approach to the integration of high-quality photodetectors on a silicon waveguide circuit, the use of III-V epitaxial material has a substantial impact on the cost of the final device. Therefore, the use of a low-cost technique for photodetector integration is being evaluated. It is based on the chemical synthesis of PbS nanoparticles in solution, which can then be applied to the silicon waveguide circuit by means of dip coating or spin coating [31]. The optical properties of these nanoparticles is determined by their size, due to quantum confinement effects, which can be used to control the bandgap of the resulting material [32]. While these quantum dots are surrounded by organic ligands in the solution to prevent them from clustering, these ligands are to be replaced by much shorter, inorganic ligands to allow efficient current transport in the

deposited quantum dot film. Recently, such a ligand exchange process was developed, leading to the demonstration of PbS-based photoconductors integrated on a silicon wafer [31,33]. A microscope image of a patterned quantum dot film on an interdigitated electrode pattern is shown in Figure 9(a). 10 nm PbS quantum dots are used to achieve an exciton transition at wavelengths beyond 2 μm , as shown in Figure 9(b). Given the fact that carriers can get trapped in quantum dot surface states, the exciton lifetime in these dots is large, which leads to a substantial internal gain in these devices (given by the ratio between the exciton lifetime and the carrier transit time between two electrodes). However, saturation of the trap states leads to a reduced gain at increasing input power levels. The measured responsivity under surface normal illumination of the photoconductor (at 10 V bias) with increasing input power is shown in Figure 9(c).

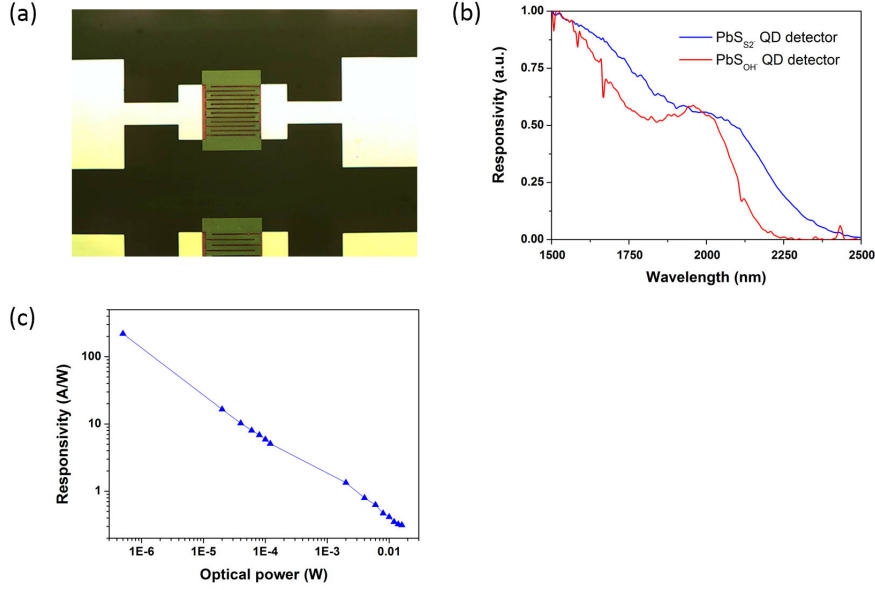


Figure 9: (a) Microscope image of a PbS nanoparticle photoconductor integrated on a silicon wafer. (b) Absorption spectrum of the PbS nanoparticle photoconductor showing the first exciton transition of 10 nm diameter PbS nanoparticles. (c) Photoconductor responsivity as a function of optical input power

7. Conclusions

The development of silicon-based photonic integrated circuits for mid-infrared spectroscopic sensing applications is described in this paper. Both passive waveguide circuits (for linear and nonlinear applications) providing low-loss waveguides and wavelength filtering functions as well as active functionality based on the heterogeneous integration of other materials on the silicon platform to provide photodetection in the mid-infrared are reported. Besides spectroscopic sensing applications these waveguide circuits might also find applications in next-generation telecommunication systems, in which one aims to exploit the large operational bandwidth of Thulium-based fiber amplifiers in the 2 μm wavelength range for high capacity optical communication links [34].

Acknowledgements

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